Diagnostic Strategy for Multi-value Attribute System Based on QDFS Algorithm

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Abstract—**In this paper, the problem of diagnostic strategy for multi-value attribute system is considered. Based on the principal characteristics that quasi-depth first search (QDFS) algorithm can improve the information heuristic algorithm, QDFS is used to improve the information entropy based diagnostic strategy for multi-value attribute system. Then, a new diagnostic strategy for multi-value attribute system is proposed. The theory and experiment demonstrate that, this method is much better than information entropy algorithm on optimization results and computational complexity, which can be used to design the optimal diagnostic strategy for complicated multi-value attribute systems.**

Keywords-design for testability; diagnostic strategy; QDFS; information entropy algorithm

I. INTRODUCTION

Optimization design of diagnostic strategy is an important content in design for testability, and its purpose is to design a set of test sequences, which can consume the expected test cost as little as possible to meet the accuracy of fault isolation [1]. The existing methods for diagnostic strategy optimization, such as information entropy algorithm, greedy algorithm, AO* algorithm, Rollout algorithm, and so on, are mainly based on fault-test dependency matrix to generate testing sequence. The test in dependency matrix has binary output with through and not through [2], [3]. However, binary output of the test is a simplified assumption, which describes the limited system state information. In fact, many tests have multiple outputs called multi-value test. Such as the frequency of test for vibration signal in mechanical and electrical system, which has three states with large, normal and small, corresponding to different fault states of system. Therefore, multi-value test can obtain more information of the system. The test is simplified as binary test may lose a lot of information and reduce the efficiency and accuracy of diagnosis. Therefore, an optimization method of diagnostic strategy for multi-value attribute system based on information entropy algorithm is proposed by combining the information increment of multi-value testing and multi-valued logic in literature [4]. However, the algorithm which is a local optimal search algorithm can not guarantee to search a global optimal solution and the time complexity and search efficiency of the algorithm need to be further verified. A heuristic breadth first spanning and dynamic programming algorithm (HBFS-DFC) is used to design the optimal diagnostic strategy for multi-value attribute system in literature [5], but this method will probably appear calculation explosion problem for the large scale system. The Rollout algorithm combined with information entropy algorithm is applied to solve the problem in literature [6]. The algorithm can not always obtain the global optimal solution, but it always gets more accurate results than using information entropy algorithm.

QDFS is a kind of calculation method for combinatorial optimization problems. Yang Peng applied it on optimization design of diagnostic strategy for test with binary output firstly [7]. Information entropy algorithm is a kind of commonly used heuristic algorithm. In this paper, a new optimization method of diagnostic strategy for multi-value attribute system is proposed, in which QDFS is adopted to improve information entropy algorithm. Firstly the dependency matrix and the problem of diagnostic strategy for multi-value attribute system are described. Then the principle and calculation steps of QDFS are elaborated. Finally the effectiveness of the algorithm is verified through example simulation.

II. PROBLEM FORMULATION

Assuming the multi-value attribute system has m fault states and n tests. The optimization problem of diagnostic strategy for multi-value attribute system is composed of the following components [8], [9].

1) $F=\left\{f_0,f_1,\cdots,f_m\right\}$ is a finite set of fault states with f_0 denoting the "fault-free" state of the system and $f_l\left(1\le l\le m\right)$ specifying the different fault states of the system;

2) $P=\left\{p\left(f_0\right),p\left(f_1\right),\cdots,p\left(f_m\right)\right\}$ is the a priori probability set associated with the set of fault states F ;

3) $T=\{t_1,t_2,\cdots,t_n\}$ is a finite set of n available tests and $C=\{c_1,c_2,\cdots,c_n\}$ is the set of test costs measured in terms of time, manpower requirements, or other economic factors, where c_j is the cost of applying test t_j.

4) $D=\lfloor d_{ij} \rfloor$ is multi-value matrix of dimension $m\times n$ which represents the relationship between the set of fault states F and the set of tests T, where d_{ij} denoting test t_j for the detection of fault state f_i attribute. The value of d_{ij} may be any integer from 0 to $k-1$. As shown in TABLE I.

TABLE I. DEPENDENCY MATRIX FOR MULTI-VALUE ATTRIBUTE SYSTEM

Fault States	t_1	t_2	$\cdots$	t_n	Fault Probabilities
	c_1	c_2	$\cdots$	c_n	
f_0	d_{01}	d_{02}	$\cdots$	d_{0n}	$p(f_0)$
f_1	d_{11}	d_{12}	$\cdots$	d_{1n}	$p(f_1)$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$
f_m	d_{m1}	d_{m2}	$\cdots$	d_{mn}	$p(f_m)$

Optimization design of diagnostic strategy for multi-value attribute system is a method that selecting a set of test from test sets to make each fault state of the system can be identified and the expected test cost as small as possible. Calculation formula of the expected test cost is as follows [10].

$$J=\sum_{i=1}^{m}\left\{\sum_{j=1}^{|p_i|}c_{p_i[j]}\right\}p(f_i) \tag{1}$$

where p_i is a test sequence used to isolate fault state f_i and $|p_i|$ is the capacity of the test sequence p_i.

III. DIAGNOSTIC STRATEGY FOR MULTI- VALUE ATTRIBUTE SYSTEM

A. Diagnostic Strategy Based on Information Entropy Algorithm

Assuming $T=\{t_1,t_2,\cdots,t_n\}$ is a set of available tests of the system. According to the result of test t_j, the fault state F of the system can be divided into k subsets, respectively it is $F_{j0},F_{j1},\cdots,F_{j(k-1)}$. According to information theory, the information about F provided by t_j as follows [2].

$$IG(F;t_j)=-\sum_{v=0}^{k-1}p(F_{jv})\log_2 p(F_{jv}) \tag{2}$$

The more information is provided by the test, the more conducive to the fault isolation. At the same time, the small cost of the test should be used during testing. According to the existing information heuristic strategy, it takes the ratio of the information about fault state provided by the test and the cost of the test as the basis of test selection [2].

$$k=\arg\max_j\left\{IG(F;t_j)/t_j\right\} \tag{3}$$

Diagnostic strategy based on information entropy algorithm means that the test t_q which is the highest ratio of information and cost should be selected continuously from available test sets, until all fault states have been isolated and the diagnostic tree have been established.

The specific calculation steps are as follows:

1) Assuming the set of fault states is $x=F$ and the set of tests is $t=T$. F and T is the initial set of fault states and tests respectively.

2) For each test t_j from set t corresponding to set x, the probability of k subsets divided by test t_j is calculated respectively as follows:

$$p(x_{jv})=\sum_{f_i\in x_{jv}}p(f_i),\quad j=0,1,\cdots,k-1 \tag{4}$$

3) According to formula (2) to calculate the information provided by each test t_j from set t.

4) According to formula (3) to select a test t_q from set t which make the ratio of the information and test cost to the highest.

5) Use test t_q to divide set x into k subsets. Then update the probability of each subset using following formula:

$$p'(f_i)=\frac{p(f_i)}{\sum_{f_i\in x_{qv}}p(f_i)},\quad v=0,1,\cdots,k-1 \tag{5}$$

6) To re-take the set x as each test subset, and set t is the initial set after removing test t_q. Then repeat step 2) to step 5) until the number of elements in test subset is not more than one.

B. Diagnostic Strategy Based on QDFS Algorithm

QDFS is a one step forward backtracking algorithm based on information entropy algorithm [7]. QDFS algorithm is used to improve information entropy algorithm to design the diagnostic strategy for multi-value attribute system in this section.

The specific calculation steps are as follows:

1) Assuming the set of fault states is $x=F$ and the set of tests is $t=T$. F and T are the initial set of fault states and tests respectively.

2) Using each test t_j from set t to divide set x into k subsets, respectively it is $\{x_{j0},x_{j1},\cdots,x_{j(k-1)}\}$.

2.1) Using formula (4) to calculate probability of each subset.

2.2) To each subset, using formula (6) to update its probability. Then using information entropy algorithm to design diagnostic strategy for each subset .A temporary diagnostic tree D_j which take t_j as the first test is established.

$$p'(f_i) = \frac{p(f_i)}{\sum_{f_i \in x_{jv}} p(f_i)}, \quad v = 0, 1, \cdots, k-1 \tag{6}$$

2.3) Using formula (7) to calculate diagnostic information of unit test cost for set x provided by temporary diagnostic tree D_j.

$$k^* = \arg\max_j \left\{ IG(x; D_j) / COST(x; D_j) \right\} \tag{7}$$

where $IG(x; D_j)$ denotes diagnostic information provided by temporary diagnostic tree D_j and $COST(x; D_j)$ denotes the average cost of temporary diagnostic tree D_j. $IG(x; D_j)$ and $COST(x; D_j)$ are calculated by formula (8) and (9) respectively.

$$IG(x; D_j) = -\sum_{k=1}^{l_j} \left(\frac{p(x_{jk})}{p(x)} \log_2 \frac{p(x_{jk})}{p(x)} \right) \tag{8}$$

where $\{x_{j1}, x_{j2}, \cdots, x_{jl_j}\}$ denotes a set of l_j leaf nodes in D_j. One of the leaf nodes may be single fault or ambiguity group consist of some faults, and the probability of them is $\{p(x_{j1}), p(x_{j2}), \cdots, p(x_{jl_j})\}$.

$$COST(x; D_j) = \sum_{k=1}^{l_j} \left(\frac{p(x_{jk})}{p(x)} \sum_{i=1}^{|D_{j(k)}|} c_{D_{j(k)}[i]} \right) \tag{9}$$

where $D_{j(k)}$ denotes the test sequence from root node t_j to leaf node x_{jk} of diagnostic tree D_j, and $|D_{j(k)}|$ denotes the length of test sequence $D_{j(k)}$, and $c_{D_{j(k)}[i]}$ denotes the cost of i th test in test sequence $D_{j(k)}$.

3) Choose the test t_q which has the max diagnostic information of unit test cost for set x.

4) Use test t_q to divide set x into k subsets, respectively it is $x_{q0}, x_{q1}, \cdots, x_{q(k-1)}$. Then update the probability of each subset using formula (5).

5) To re-take the set x as each test subset, and set t is the initial set after removing test t_q. Then repeat step 2) to step 4) until the number of elements in test subset is not more than one.

Thus the selected tests compose the optimal test sequence.

IV. APPLICATION

The example is took from literature [5], and is used to analysis optimization design of diagnostic strategy for multi-value attribute system based on QDFS algorithm. In this system, there are 6 fault states and 4 tests. The given dependency matrix along with the probability of fault states and test costs is shown in TABLE II.

TABLE II. DEPENDENCY MATRIX FOR SYSTEM

Fault States	t_1	t_2	t_3	t_4	Fault Probabilities
	9	12	15	8	
f_0	1	1	1	0	0.70
f_1	2	1	2	1	0.01
f_2	3	0	0	0	0.02
f_3	1	0	0	0	0.10
f_4	1	0	3	0	0.05
f_5	2	0	1	1	0.12

When test t_1 is selected at first, the set F can be divided into 3 subsets corresponding to $\{f_0, f_3, f_4\}$, $\{f_1, f_5\}$ and $\{f_2\}$. The probability of $\{f_0, f_3, f_4\}$ is 0.70+0.10+0.05= 0.85, $\{f_1, f_5\}$ is 0.01+0.12=0.13 and $\{f_2\}$ is 0.02.

First, we establish the diagnostic tree by using information entropy algorithm for 3 subsets in turn. Thus the test sequence of f_0 is $\{t_1, t_2\}$, the test sequence of f_3 and f_4 is $\{t_1, t_2, t_3\}$, the test sequence of f_1 and f_5 is $\{t_1, t_2\}$ and the test sequence of f_2 is t_1.

Then, we calculate the diagnostic information and average test cost of temporary diagnostic tree D_1.

$$\begin{aligned} IG(F; D_1) &= -(0.70\log_2 0.70 + 0.10\log_2 0.10 + 0.05\log_2 0.05 + \\ &\quad 0.01\log_2 0.01 + 0.12\log_2 0.12 + 0.02\log_2 0.02) \\ &= 1.4549 \end{aligned}$$

$$\begin{aligned} COST(F; D_1) &= 0.70 \times 21 + 0.10 \times 36 + 0.05 \times 36 + \\ &\quad 0.01 \times 21 + 0.12 \times 21 + 0.02 \times 9 \\ &= 23.01 \end{aligned}$$

Therefore, the diagnostic information of unit test cost for set F provided by temporary diagnostic tree D_1 is calculated as follows.

$$k_1 = 1.4549/23.01 = 0.0632$$

In the same way, we select t_2, t_3 and t_4 respectively to establish temporary diagnostic tree for fault state set F, as shown in Fig. 1. Then calculate respectively the diagnostic information of unit test cost for set F provided by temporary diagnostic tree.

$$k_2 = 0.0645; \quad k_3 = 0.0643; \quad k_4 = 0.0616$$

In Figure 1, we found the optimal test is t_2 which has the maximal diagnostic information of unit test cost for set $\{f_0, f_1, f_2, f_3, f_4, f_5\}$. When test t_2 is selected, the fault state set can be divided into $\{f_0, f_1\}$ and $\{f_2, f_3, f_4, f_5\}$, and the remaining test set is $\{t_1, t_3, t_4\}$ with removing test t_2. However, fault state set $\{f_0, f_1\}$ can be isolated by test t_4 only. We continue to use QDFS algorithm to establish the temporary diagnostic tree for set $\{f_2, f_3, f_4, f_5\}$ and found the optimal test is t_1 which has the maximal diagnostic information of unit test cost for set $\{f_2, f_3, f_4, f_5\}$. Thus set $\{f_2, f_3, f_4, f_5\}$ is divided into $\{f_2\}$, $\{f_5\}$ and $\{f_3, f_4\}$, however set $\{f_3, f_4\}$ can be isolated by test t_3 only. The final diagnostic strategy is shown in Figure 2, in which the total test cost expected is 22.54 by using QDFS algorithm and 23.01 by using information entropy algorithm. The diagnostic strategy established by using QDFS algorithm is the same as the diagnostic strategy established by using Rollout algorithm in literature [6].

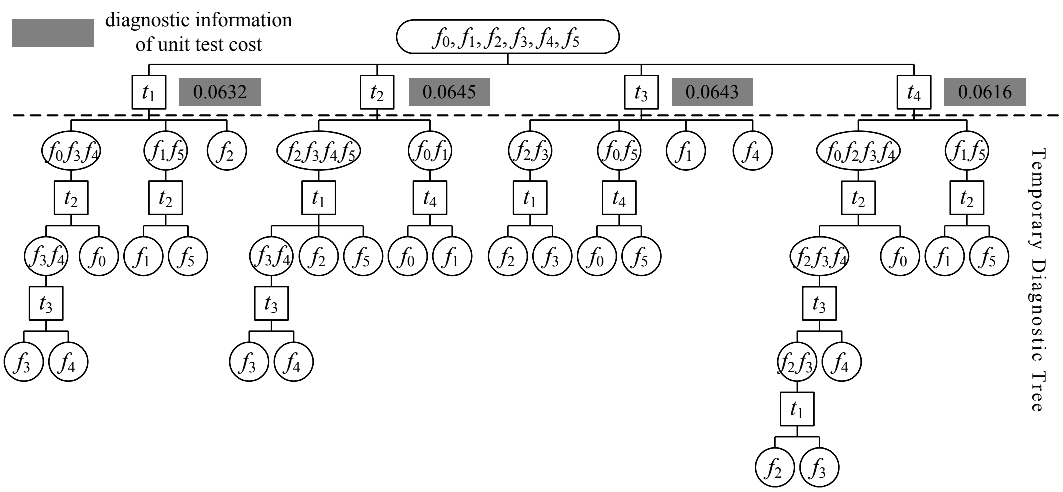
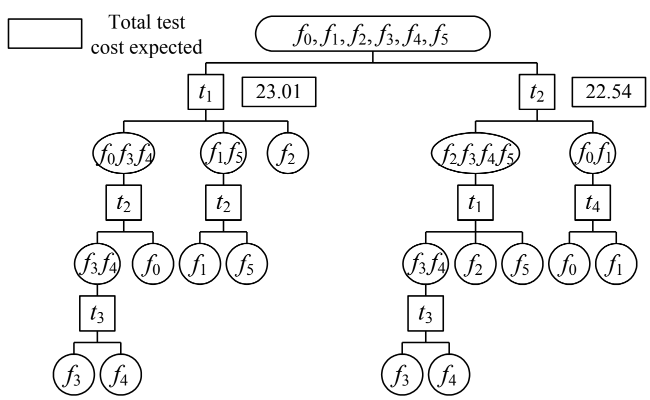


Figure 1. Temporary diagnostic tree generated by QDFS algorithm.



（a）Information entropy algorithm （b）QDFS algorithm

Figure 2. Optimization design of diagnostic strategy for example.

V. COMPUTATIONAL COMPLEXITY ANALYSIS

The most complicated situation of diagnostic strategy optimization problem is that the child node generated from node can continue generate child node until all tests are selected in the process of establishing diagnostic tree.

Under the most complicated situation, there are n layers of nodes generated by information entropy algorithm during establishing diagnostic tree. Among them, the number of nodes in layer i is $u_i = k^{i-1}(n+1-i)$ and the number of all nodes is

$$\text{Sum} = \left(\frac{k}{k-1}\right)^2 k^{n-1} - \frac{k}{k-1} n - \frac{k}{(k-1)^2}$$

Therefore, the computational complexity of information entropy algorithm is $O\left(k^{n-1}\right)$.

There are the same n layers of nodes generated by QDFS algorithm during establishing diagnostic tree. In first $n-1$ layers, the number of nodes in layer i is

$$u_i = \left(\left(\frac{k}{k-1} \right)^2 k^{n-1-i} - \frac{n-i}{k-1} - \frac{k}{(k-1)^2} \right) k^i \left(n+1-i \right).$$

The number of nodes in layer n is $u_n = k^{n-1}$. Therefore, the computational complexity of QDFS algorithm is $O\left(n^2 k^{n-1}\right)$.

VI. CONCLUSION

During the optimization design of diagnostic strategy for multi-value attribute system, the global optimal algorithm is not suitable for complex multi-value attribute system because of the explosion problem of calculation. In this paper, the optimization design of diagnostic strategy for multi-value attribute system based on QDFS algorithm is established which uses QDFS algorithm to improve information entropy algorithm. Through the experiment analysis, it demonstrates that the total test cost expected is obtained by QDFS algorithm no more than information entropy algorithm, and the calculation time of QDFS algorithm within an acceptable range. Therefore, QDFS algorithm can be used to design optimal diagnostic strategy for complex multi-value attribute system.

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